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IN THE UNITED STATES  
PATENT & TRADEMARK OFFICE

Inventor : Dina Katsir et al.  
Serial No. : 10/730,537  
Filed : 12/05/2003  
For : ELECTRODES FOR ELECTROLYTIC CAPACITORS AND METHOD FOR  
PRODUCING THEM  
Group Art Unit: 1742  
Examiner : Unassigned  
Docket No. : ACKT 336/8.3

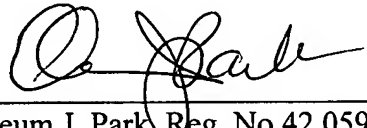
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Filed herewith is a certified copy of priority document, Israel patent application  
153,289 filed 12/05/2002, for the above identified U.S. patent application.

Respectfully submitted:

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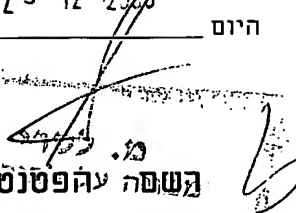
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	תאריך : Date 05-12-2002 הוקדם/נדחה Ante/Post-dated

חוק הפטנטים, תשכ"ז - 1967  
PATENT LAW, 5727-1967

בקשה לפטנט  
Application for Patent

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2. דינה קציר

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(בעברית)

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מבקשת פטנט from Application	לבקשה / לפטנט to Patent / Appl	מספר/סימן Number / Mark	תאריך Date	מדינת האגוד Convention Country
No. _____ מס' _____ dated _____ מיום _____	No. _____ מס' _____ dated _____ מיום _____			
פנוי כח: כללי / מיוחד / - רצוף בזה / עוד יוגש P.O.A. : general / individual-attached / to be filed later הוגש בענין 135550 filed in case				
המען למסירת מסמכים בישראל: ירמיהו מ. בן-דוד ושות' בע"מ ת.ד. 45087 Address for Service in Israel: 91450 ירושלים Jeremy M. Ben-David & Co. Ltd. POBox 45087 Jerusalem 91450				
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ELECTRODES FOR ELECTROLYTIC CAPACITORS AND METHOD FOR  
PRODUCING THEM

Acktar Ltd.

אקטר בע"מ

ACK 336/8.1

## FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to electrodes for electrolytic capacitors and, to a method for producing such electrodes, particularly anodes but also cathodes, having increased effective surface area. The invention moreover relates to anodized electrodes which comprise non-cylindrical pores having a branched morphology.

Electrical capacitors are elementary electrical devices, intended to accumulate a static electric charge on their plates. One plate is metallic and the other plate is an electrolyte. Intervening between the two plates is a dielectric consisting of a surface oxide coating on the metal plate. Conventionally, the metal plate on which the dielectric coating is formed is referred to as the anode. The term "anode" is used herein to refer both to the metal plate itself and to the combination of the metal plate with the dielectric coating. It will be clear from the context which meaning of "anode" is intended.

To increase substantially the surface area of a metal electrode, and consequently the value of its specific capacitance, etching of a metal substrate has been applied to create a system of numerous pits, see for example US Patent No. 4,537,665 (Nguyen, et al.) which describes manufacture of low-voltage aluminum foil electrolytic capacitor electrodes including etching the foil, cleaning and anodizing it, the cleaned foil being thermally treated at about 595-650°C, and then anodizing the treated foil in an adipate electrolyte.

In other prior etching technologies, the etching solutions typically contain  $\text{Cl}^-$  ions, see e.g. US Patent No. 6,168,706 Hemphill, et al.), which employs hydrated  $\text{AlCl}_3$ ,  $\text{HCl}$ ,  $\text{H}_2\text{SO}_4$  and  $\text{HClO}_4$  or  $\text{ClO}_4^-$ . It is believed, however, that the presence of halogens in etching solutions is liable to cause serious ecological problems, complex and high cost disposal and in addition inhibit anodization.

To overcome such disadvantages and also to reduce capacitor size by using thinner Al foil recently, vacuum deposition has been proposed for increasing the surface area of foil electrodes. Thus, e.g., Drake, in US Patent No. 4,309,810, teaches vacuum deposition of a metal vapor at a low angle onto a foil substrate, and presents an example of the deposition of aluminum

on aluminum to give a columnar structure. However, Drake's foil has been found to be too brittle for use in electrolytic capacitors, because the columns break when the foil is rolled into a cylindrical roll, one of the standard procedures in the manufacture of electrolytic capacitors.

Another method of electrode manufacture by an improved vacuum deposition method, providing high surface area values, has been described by Katsir et al., in US Patent No. 6,287,673. This method utilizes condensation of metal vapor on a thin conducting substrate in an atmosphere of low-pressure inert gas/oxygen mixture, so as to produce a porous coating structure having a high surface area. Aluminum is generally a suitable material to be selected from the family of valve metals, due to its high electrical conductivity, low cost of high-purity aluminum foil and bulk metal, good dielectric properties of alumina and other technological advantages. The required oxide film is produced by electrolytically anodizing the obtained coating, by DC current in a non-solvent or weakly solvent electrolyte, such as the ammonium salts of boric, citric, oxalic and adipic acids or mixtures thereof.

The process of anodizing foils is accompanied, unavoidably, by gradual filling of its pores by oxide due to increasing thickness of the alumina layer, and of course filled pores do not contribute positively to the surface area. It is clear that the width and depth of pores are critical parameters of the obtained coating. If the initial sizes of trench-like pores are not large enough, the process of filling the pores during anodization leads to rapidly decreasing capacitance of the desired electrodes. On the other hand, the capacitance also decreases if the pore size is too large. For anode foils, it is necessary that pore diameter is larger than the thickness of the dielectric coating (e.g.  $\text{Al}_2\text{O}_3$ ) made by the anodization voltage. By way of example, a simplified estimation for  $\text{Al}_2\text{O}_3$  thickness for 60 V forming voltage, i.e. the final voltage, is as follows: the  $\text{Al}_2\text{O}_3$  thickness will be  $14 \text{ \AA per volt} \times 60 \text{ volt} = 840 \text{ \AA}$ . Thus, it is necessary that – in this illustration – pore diameter will be larger than  $840 \text{ \AA}$ , and pore sizes with a smaller diameter will not contribute to the capacitance because the pores will be filled up by  $\text{Al}_2\text{O}_3$ . As the thickness of the dielectric layer increases, the capacitance decreases, but with a consequent increase in the working voltage of the capacitor.

Vacuum deposition methods *per se* are limited in their ability to create large pores. Therefore, only electrodes with an extremely low-voltage range can be manufactured using such known methods.

In US 20020149902 A1, published October 17, 2002, there is described an electrode foil for an aluminum electrolytic capacitor, comprising a plurality of main pits formed by etching on both surfaces of an aluminum foil to extend from the surfaces in a thickness direction of the foil, and sub pits branched away from the main pits and along the length of the main pits, as well as a multi-step etching procedure for creating and enlarging both main pits and sub pits. In practice, the main pits are vertical and have a uniform and apparently cylindrical cross section, while the sub-pits are formed perpendicularly to the longitudinal axis of the main pits and appear also to have a uniform and apparently cylindrical cross section. Use in this procedure of chlorine-containing etchants necessitated a dechlorination step.

It would thus be desirable to provide a method for manufacturing electrolytic capacitor electrodes and to obtain (for example) anode foils for aluminum electrolytic capacitors with increased values of specific capacity, suitable for a broader in-use voltage range up to and more than 60 volts.

It is accordingly an object of the invention to provide electrolytic capacitor electrodes based on vacuum deposition techniques, but with increased values of specific capacity, and a method for making such electrodes.

Other objects of the invention will appear from the description which follows.

The entire contents of the above-mentioned US Patents and published US Patent Application are incorporated by reference herein.



## SUMMARY OF THE INVENTION

The present invention accordingly provides in one aspect, method for preparing an anodized electrode comprising the sequential steps of:

- (1) providing a substrate;
- (2) coating the surface of the substrate by vacuum deposition thereon of a porous coating comprising at least one substance selected from valve metals, valve metal oxides and mixtures thereof;
- (3) increasing the effective surface area of the porous coating; and
- (4) producing electrolytically at least one anodized valve oxide layer overlaying the surface of the porous coating.

Moreover, the present invention provides in another aspect, a method for preparing an anodized electrode which includes pores having a branched morphology, comprising the sequential steps of:

- (1) providing a metallic foil substrate;
- (2) coating the surface of the substrate by vacuum deposition thereon of aluminum vapor in presence of a minor amount of oxygen such that a porous layer, consisting essentially of an aluminum metal component and an aluminum oxide component, is deposited on the substrate;
- (3) increasing the effective surface area of the porous coating by electrolytic anodization in presence of an electrolyte which comprises a saturated dicarboxylic acid salt selected from the ammonium and alkali metal salts, and removing thus-formed valve metal oxide(s), as well as at least part of the aluminum oxide component, by use of a halogen-free chemical etchant *in situ* or in a discrete subsequent sub-step; and
- (4) producing electrolytically at least one anodized aluminum oxide layer overlaying the surface of the porous coating.

In still another aspect, the invention provides an anodized electrode comprising:

- a substrate;
- a porous coating on the surface of the substrate produced by vacuum deposition thereon, the porous coating comprising at least one substance selected from valve metals, valve metal oxides and mixtures thereof; and
- at least one electrolytically produced anodized layer selected from valve metal oxides and mixtures thereof;

wherein in the porous coating, the effective surface area has been increased prior to deposition of the at least one anodized layer.

In the method(s) of the invention, the effective surface area increase of the porous coating may be achieved by increasing the total pore volume of the porous coating, and/or by increasing the average pore width in the porous coating. The term "average pore width" means the average pore width at the surface of the vapor deposited coating.

Furthermore, the invention provides in yet another aspect, an anodized electrode which comprises non-cylindrical pores having a branched morphology, and in particular, wherein at least some of the pores are generally configured as inverted cones.

It has been found that the present invention (as compared with non-etching) is capable of achieving an increase in the specific capacitance of manufactured foils, of substantially 100% or more, especially for relatively large values of forming voltage in a range from 40 up to 80 volts.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 shows schematically in section, a foil substrate on which there has been vapor deposited (VD), illustratively, a layer of Al and/or Al oxide.

Fig. 2 shows schematically in section, an embodiment of the invention as applied to the substrate + VD layer, depicted in Fig. 1.

Fig. 3 is a graph which compares for three foils, a specific parameter ( $\xi$ ) proportional to specific capacitance, in relation to the final anodization voltage.

Fig. 4 shows schematically in section, an embodiment of the invention in which pores have a branched morphology.

#### DETAILED DESCRIPTION OF THE INVENTION

The anodized electrode of the present invention is preferably further characterized by at least one of the following features:

- (a) the electrically conductive substrate is a metallic foil substrate;
- (b) the initial layer comprises at least one member selected from aluminum, aluminum oxide and mixtures thereof;

- (c) the initial layer is a vapor deposited layer
- (d) the final layer or layers comprise(s) aluminum oxide;
- (e) the pore volume enlargement has been effected by oxidizing the surface of the initial layer and removing thus-formed valve metal oxide(s).

Also, in the method(s) of the invention, it is preferable that at least one of the following conditions applies:

- (a) the substrate is an electrically conductive substrate;
- (b) the porous coating comprises at least one member selected from aluminum, aluminum oxide and mixtures thereof;
- (c) the at least one electrolytically produced layer comprises aluminum oxide;
- (d) the effective surface area increase has been implemented by at least one procedure selected from:
  - electrochemical etching, and
  - oxidizing the surface of the porous layer followed by removal of thus formed oxide;
- (e) prior to deposition of the porous coating, the surface of the substrate has been subjected to a roughening procedure selected from mechanical, chemical and electrochemical procedures;
- (f) the vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr,
- (g) the vacuum deposition is carried out in an inert gas atmosphere in presence of a minor amount of oxygen;
- (h) following step (4), the product is thoroughly rinsed with a liquid selected from distilled and de-ionized water, and then dried.

In the method(s) of the invention, the pore volume enlarging step (ii) is preferably effected by electrolytic anodization in presence of an electrolyte which comprises a saturated dicarboxylic acid salt (e.g. an adipate) selected from the ammonium and alkali metal salts. Thus-formed valve metal oxide(s) are preferably removed by use of a halogen-free chemical etchant (selected, e.g., from inorganic and organic acids), either *in situ* or in a discrete subsequent sub-step. Moreover, following step (ii), the substrate having the thus-enlarged pore volume is desirably thoroughly rinsed with a liquid selected from distilled and deionized water, before proceeding to step (iii).

In a particular embodiment, step (iii) is carried out by depositing at least two electrolytically deposited layers, e.g. by effecting at least two successive anodization steps, and the product is preferably subjected to annealing prior to the last of the successive anodization steps. It is preferable also for the product to be thoroughly rinsed with a liquid selected from distilled and deionized water, prior to annealing. Moreover, it is also desirable for the product to be thoroughly rinsed with a liquid selected from distilled and deionized water, and then dried, following the last of the successive anodization steps.

From what has been stated above, and without prejudice to the scope of the invention as defined herein, it will be appreciated that the valve metal(s) preferably comprise(s) aluminum.

In a particular embodiment of the invention, vacuum deposition conditions are such – when using aluminum in presence of oxygen - that the porous layer prior to step (3) consists essentially of at least 40% (preferably 50-85%) aluminum metal, balance aluminum oxide.

The mentioned chemical etchant is preferably selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

Fig. 1 shows schematically in section, a vapor deposited (VD) layer (4) of e.g. Al and/or Al oxide, which has been deposited on a surface (8) of an Al foil substrate (2). The VD layer includes possibly trench-like pores (6) having, for illustrative purposes, a triangular section, and which have maximum width  $x$  and height  $y$ .

Fig. 2 shows schematically in section, the result of applying the present invention to the VD layer of Fig. 1, i.e., increasing the pore volume. In the illustrated embodiment, this is done by removing, by chemical etching, an Al oxide layer which had been deposited by anodization, or in other words by electrochemically oxidizing and thus eroding the surface of the VD layer. As described elsewhere in the specification, following the etching step which removes initially deposited Al oxide thus enlarging the pores, an anodized layer is then applied in one or more steps to the etched surface in order to obtain a final product. In Fig. 2, VD layer(14) has been deposited on an Al foil substrate (12) and the entire upper surface of the VD layer continuum including the pores (16) is covered by the final anodized layer 18. Resulting

from application of the present method, pores 16 now have a greater width ( $x + a$ ) than the original pores in the VD layer and a different depth  $z$ , since the etching procedure on the one hand removes surface metal, but on the other hand increases penetration of the pores, possibly even up to the interface 10 between substrate 12 and VD layer 14.

Because the specific capacitance of the present electrode foils,  $C(\text{spec}) = \mu\text{F}/\text{cm}^2$ , is nearly proportional to the thickness of the VD coating  $D$  ( $\mu\text{k}$ ) and inversely proportional to the anodized oxide film thickness  $\delta$  (nm), the withstanding voltage  $W$  of the oxide layer is proportional to  $\delta$ , so that foil quality can be estimated by means of parameter  $\xi = C(\text{spec})W/D$ . It may be assumed that the larger the values of parameter  $\xi$ , so these foils should have improved characteristics as capacitor electrodes. In Fig. 3,  $\xi$  values have been plotted against the forming (i.e. the final anodization) voltage for three foils. The triangular points denote a standard Al etched foil of Nippon Co. manufacturing; the value of  $D$  having been assumed in this case to be equal to depth of the pores. The hollow rectangular points represent typical data for an untreated VD coated foil manufactured by Acktar Ltd. The solid rectangular points represent data for an embodiment of the present invention prepared according to Example II herein. This figure shows a remarkable increase of  $\xi$  for the present invention as compared with the prior art, over a wide range of forming voltage.

In Fig. 4, illustrating an embodiment of the aspect of the invention in which the pores have a branched morphology, on substrate 20, there has been vapor deposited coating 22 containing illustrative pores 26. In the etching step, oxide in the vacuum deposited coating has been removed to form branches 28. Reference numeral 24 denotes residual surface oxide which remains after etching.

## DESCRIPTION OF PRESENTLY PREFERRED EMBODIMENTS

The pore volume enlargement which is a feature of the present invention can be achieved in a number of ways.

A high-purity aluminum substrate, after reactive deposition of Al/ Al<sub>2</sub>O<sub>3</sub> in an inert gas atmosphere having a pressure of between about 10<sup>-3</sup> atm. and about 10<sup>-2</sup> atm., containing also a partial pressure of oxygen (see US Patent No. 6,287,673), is anodized by DC current at an initial current density of about 2A/dm<sup>2</sup> in an aqueous solution of ammonium adipate, at a temperature of about 50°C, at a voltage up to the required in-use voltage. This process is stopped at a current density near 40mA/dm<sup>2</sup>. Thorough rinsing of the foil by deionized water is followed by chemical etching. This may be effected e.g., in an aqueous solution of a phosphoric/chromic acid mixture, for about 2-3 minutes at a solution temperature of about 40°C. In an alternative embodiment, which is more acceptable from an ecological point of view, etching is carried out using a carboxylic acid (such as oxalic acid) in aqueous solution, at temperature of 50-80°C, e.g. about 60°C, for 15-45 minutes, e.g. about 30 minutes. In yet another embodiment, initial anodization is carried out with aqueous carboxylic acid salt such as ammonium adipate, while etching is effected virtually simultaneously by the presence of 0.01M to 0.02M (e.g. 0.014M) oxalic acid dissolved in the electrolytic bath, the operation being carried out at about 50°C. The anodized coating may be stabilized for 15 minutes after the moment of current has broken down [PLEASE EXPLAIN]. The preparation process may be completed by annealing at about 500°C for about 2 minutes, and further anodizing for about 2 minutes under previously stated conditions.

The invention will be illustrated by the following non-limiting Examples.

### Example I

An anodized foil electrode is manufactured by the following stepwise procedure:

1. A high-purity aluminum foil substrate is subjected to reactive deposition of Al/ Al<sub>2</sub>O<sub>3</sub> in an inert gas atmosphere having a pressure of between about 10<sup>-3</sup> atm. and about 10<sup>-2</sup> atm., containing also a partial pressure of oxygen, as described in US Patent No. 6,287,673.

2. The product of step 1 is anodized by DC current at an initial current density of about  $2\text{A/dm}^2$  in an  $0.83\text{M}$  aqueous solution of ammonium adipate, at a temperature of about  $50^\circ\text{C}$ . Anodization is continued up to 15 minutes past current break out.
3. The product of step 2 is thoroughly rinsed with deionized water.
4. The product of step 3 is etched by immersion in an aqueous solution containing  $\text{H}_3\text{PO}_4$  (35g/l OF 80% acid) and chromic acid (20 g/l  $\text{CrO}_3$ ), at  $40^\circ\text{C}$  for 2.5 minutes.
5. The product of step 4 is anodized under the conditions of step 2.
6. The product of step 5 is thoroughly washed with deionized water.
7. The product of step 6 is annealed at about  $500^\circ\text{C}$  in a flow of hot air, for about 2 minutes. and further anodizing for about 2 minutes under previously stated conditions.
8. The product of step 7 is anodized under the conditions of step 2 for about 2 minutes.
9. The product of step 8 is thoroughly washed with deionized water, and dried in a flow of hot air.

In this Example, and in Examples II and III, it is to be understood that the procedure is carried out in a continuous manner by passage of Al foil in roll form from one step to the next step.

#### Example II

This is carried out as in Example I, except that etching step 4 is carried out by immersion the product of step 3 is etched by immersion in an  $0.3\text{M}$  aqueous solution of oxalic acid at  $60^\circ\text{C}$  for about 30 minutes.

#### Example III

This is carried out as in Example I, except that steps 2-4 are replaced by the following procedure (virtually simultaneous initial anodization and etching). The product of step 1 is immersed in a single bath containing an aqueous solution which is  $0.83\text{M}$  in respect of ammonium adipate and  $0.14\text{M}$  in respect of oxalic acid. Current density, temperature and time if this operation are as stated in step 2 of Example I. The foil is thoroughly rinsed with deionized water, following which the operations described in steps 5-9 of Example I are carried out.

#### Example IV: Determination of Pore Volume Enlargement

Method. Two identical samples of VD foils NN 464/1/11/1 and 464/1/11/2 based on an Al foil substrate of thickness 65  $\mu\text{m}$  and whole area 12.38  $\text{cm}^2$ , were coated on both sides by Al /Al<sub>2</sub>O<sub>3</sub> of thickness 20  $\mu\text{m}$  each side, as described in US Patent No. 6,287,673. The area of each coated surface was 11.91  $\text{cm}^2$ . Both samples were formed (anodized) for 10 minutes in an ammonium adipate solution at forming voltage 21 volts, forming current 0.5A, and electrolyte temperature 85°C. The area of samples, soanodized was 10  $\text{cm}^2$ . The samples were then washed with deionized water, dried and weighed.

In order to compare pore volumes, the second sample prior to final anodization was etched in an oxalic acid solution 0.3M at 60°C during 15 minutes, and then anodized, washed, dried and weighed, as above.

The samples were now immersed in heated oil (TKO-19+) at 100°C, with a specific gravity 0.87  $\text{g}/\text{cm}^3$ . Excess oil was carefully removed, and both samples were weighed. It is believed that substantially all pores were filled entirely by the heated oil.

#### Calculations

The first (non-etched) foil sample was found to have absorbed 8.9 mg oil, i.e.  $8.9/0.87=10.22 \text{ mm}^3$ . oil, distributed on an area of 11.91  $\text{cm}^2$ . Therefore the oil volume absorbed on the anodized area of the sample (10  $\text{cm}^2$ ) is  $10.22 \times 10/11.91 = 8.58 \text{ mm}^3$ . Reduction of the pore volume caused by anodization is related to an estimated wall thickness difference of 15 nm, and is approximately  $5.55 \text{ mm}^3$ , so that the pore volume before anodization was equal to  $5.55+8.58=14.13 \text{ mm}^3$ . Because of the volume of coating under treatment (for two sides of substrate) is approximately  $40 \text{ mm}^3$ , the degree of porosity of the initial sample is  $100 \times 14.13/40 = 35.3\%$

Similar evaluation of the porosity of the second (etched and anodized) foil sample, which was found to have absorbed  $19.65^3 \text{ mm}$  oil, affords an estimated 41.2% porosity.



### Conclusion

In this exemplified embodiment of the present invention, the additional etching step almost doubled the pore volume and increased the degree of porosity of the sample about 20%.

While particular embodiments of the invention have been particularly described hereinabove, it will be appreciated that the present invention is not limited thereto, since as will be readily apparent to skilled persons, many modifications or variations can be made. Such modifications or variations which have not been detailed herein are deemed to be obvious equivalents of the present invention.

## CLAIMS

1. A method for preparing an anodized electrode comprising the sequential steps of:
  - (1) providing a substrate;
  - (2) coating the surface of the substrate by vacuum deposition thereon of a porous coating comprising at least one substance selected from valve metals, valve metal oxides and mixtures thereof;
  - (3) increasing the effective surface area of said porous coating; and
  - (4) producing electrolytically at least one anodized valve oxide layer overlaying the surface of said porous coating.
2. A method according to claim 1, wherein said effective surface area increase of said porous coating is achieved by at least one of the following:
  - increasing the total pore volume of said porous coating;
  - increasing the average pore width in said porous coating.
3. A method according to claim 1, which is further characterized by at least one of the following features:
  - (a) said substrate is an electrically conductive substrate;
  - (b) said porous coating comprises at least one member selected from aluminum, aluminum oxide and mixtures thereof;
  - (c) said at least one electrolytically produced layer comprises aluminum oxide;
  - (d) said effective surface area increase has been implemented by at least one procedure selected from:
    - electrochemical etching, and
    - oxidizing the surface of said porous layer followed by removal of thus formed oxide;
  - (e) prior to deposition of said porous coating, the surface of said substrate has been subjected to a roughening procedure selected from mechanical, chemical and electrochemical procedures;
  - (f) said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr,

(g) said vacuum deposition is carried out in an inert gas atmosphere in presence of a minor amount of oxygen;

(h) following step (4), the product is thoroughly rinsed with a liquid selected from distilled and de-ionized water, and then dried.

4. A method according to claim 3, which is further characterized by at least one of the following features:

(A) said electrically conductive substrate is a metallic foil substrate;

(B) step (3) is implemented by electrolytic anodization and simultaneously or subsequently removing electrolytically formed valve metal oxide.

5. A method according to claim 4, wherein step (4) is carried out by forming at least two anodized layers, and the product is subjected to annealing prior to the last of said at least two anodization steps.

6. A method according to claim 5, wherein the product is thoroughly rinsed with a liquid selected from distilled and de-ionized water, prior to said annealing.

7. A method according to claim 4, wherein said substrate is a metallic foil substrate; in step (2) said at least one valve metal comprises aluminum; in step (3) said increasing is implemented by oxidizing the surface of said initial layer by anodization in presence of an electrolyte which comprises a saturated dicarboxylic acid salt selected from the ammonium and alkali metal salts, and removing thus-formed valve metal oxide(s) by use of a halogen-free chemical etchant *in situ* or in a discrete subsequent sub-step; and in step (4) said at least one layer comprises aluminum oxide.

8. A method according to claim 7, wherein step (4) is carried out by forming at least two anodized layers, and the product is subjected to annealing prior to the last of said at least two anodization steps.

9. A method according to claim 7, wherein at least one of the following features applies:

said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr. in presence of a minor amount of oxygen;

said electrolyte comprises a salt selected from the ammonium and alkali metal adipates;

said chemical etchant is selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

10. A method according to claim 8, at least one of the following features applies:

said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr. in presence of a minor amount of oxygen;

said electrolyte comprises a salt selected from the ammonium and alkali metal adipates;

said chemical etchant is selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

11. A method according to claim 4, wherein said substrate is a metallic foil substrate; in step (2) said at least one valve metal consists essentially of aluminum and said vapor deposition is carried out in presence of a minor amount of oxygen such that said porous layer consists essentially of aluminum metal and aluminum oxide; in step (3) said increasing is implemented by oxidizing the surface of said initial layer by anodization in presence of an electrolyte which comprises a saturated dicarboxylic acid salt selected from the ammonium and alkali metal salts, and removing thus-formed valve metal oxide(s) by use of a halogen-free chemical etchant *in situ* or in a discrete subsequent sub-step; and in step (4) said at least one layer comprises aluminum oxide.

12. A method according to claim 11, wherein step (4) is carried out by forming at least two anodized layers, and the product is subjected to annealing prior to the last of said at least two anodization steps.

13. A method according to claim 11, wherein at least one of the following features applies:

said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr.;

said vacuum deposition conditions are such that said porous layer prior to step (3) consists essentially of at least 40% aluminum metal, balance aluminum oxide;

said electrolyte comprises a salt selected from the ammonium and alkali metal adipates;

said chemical etchant is selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

14. A method according to claim 11, wherein at least one of the following features applies:

said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr.;

said vacuum deposition conditions are such that said porous layer prior to step (3) consists essentially of 50-85% aluminum metal, balance aluminum oxide;

said electrolyte comprises a salt selected from the ammonium and alkali metal adipates;

said chemical etchant is selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

15. A method for preparing an anodized electrode which includes pores having a branched morphology, comprising the sequential steps of:

(1) providing a metallic foil substrate;

(2) coating the surface of the substrate by vacuum deposition

thereon of aluminum vapor in presence of a minor amount of oxygen such that

a porous layer, consisting essentially of an aluminum metal component and an aluminum oxide component, is deposited on said substrate;

(3) increasing the effective surface area of said porous coating by electrolytic anodization in presence of an electrolyte which comprises a saturated dicarboxylic acid salt selected from the ammonium and alkali metal salts, and removing thus-formed valve metal oxide(s), as well as at least part of said aluminum oxide component, by use of a halogen-free chemical etchant *in situ* or in a discrete subsequent sub-step; and

(4) producing electrolytically at least one anodized aluminum oxide layer overlying the surface of said porous coating.

16. A method according to claim 15, wherein at least one of the following features applies:

said vacuum deposition is carried out in an inert gas atmosphere at a pressure about  $10^{-3}$  Torr. and about  $10^{-2}$  Torr.;

said vacuum deposition conditions are such that said porous layer prior to step (3) consists essentially of at least 40% aluminum metal, balance aluminum oxide;

said electrolyte comprises a salt selected from the ammonium and alkali metal adipates;

said chemical etchant is selected from chromic, oxalic and phosphoric acid, and mixtures thereof.

17. A method according to claim 16, wherein step (4) is carried out by forming at least two anodized layers, and the product is subjected to annealing prior to the last of said at least two anodization steps.

18. An anodized electrode comprising:

a substrate;

a porous coating on the surface of the substrate produced by vacuum deposition thereon, said porous coating comprising at least one substance selected from valve metals, valve metal oxides and mixtures thereof; and

at least one electrolytically produced anodized layer selected from valve metal oxides and mixtures thereof;

wherein in said porous coating, the effective surface area has been increased prior to deposition of said at least one anodized layer.

19. An anodized electrode according to claim 18, which is further characterized by at least one of the following features:

- (a) said substrate is an electrically conductive substrate;
- (b) said porous coating comprises at least one member selected from aluminum, aluminum oxide and mixtures thereof;
- (c) said at least one anodized layer comprises aluminum oxide;
- (d) said effective surface area increase has been implemented by oxidizing the surface of said porous layer and removing thus formed oxide;
- (e) prior to deposition of said porous coating, the surface of said substrate has been subjected to a roughening procedure selected from mechanical, chemical and electrochemical procedures.

20. An anodized electrode according to claim 19, wherein said porous coating consists essentially of aluminum and aluminum oxide and said at least one anodized layer consists essentially of aluminum oxide.

21. An anodized electrode according to claim 20, wherein prior to effective surface area increase and anodization, said porous coating consists essentially of 50-85% aluminum metal, balance aluminum oxide.

22. An anodized electrode according to claim 18, wherein said effective surface area increase had been achieved by at least one of the following:  
increasing the total pore volume of said porous coating;  
increasing the average pore width in said porous coating.

23. An anodized electrode which comprises non-cylindrical pores having a branched morphology.

24. An anodized electrode according to claim 23, wherein at least some of said pores are generally configured as inverted cones.

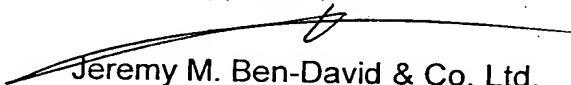
25. A method according to any of claims 1-17, and substantially as shown and described hereinabove in conjunction with any of Figs. 1-4.

26. A method according to any of claims 1-17, and substantially as shown in any of Figs. 1-4.

27. An electrode according to any of claims 18-24, and substantially as shown and described hereinabove in conjunction with any of Figs. 1-4.

28. An electrode according to any of claims 18-24, and substantially as shown in any of Figs. 1-4.

For the Applicant,



Jeremy M. Ben-David & Co. Ltd.  
ACKT 336/8.1



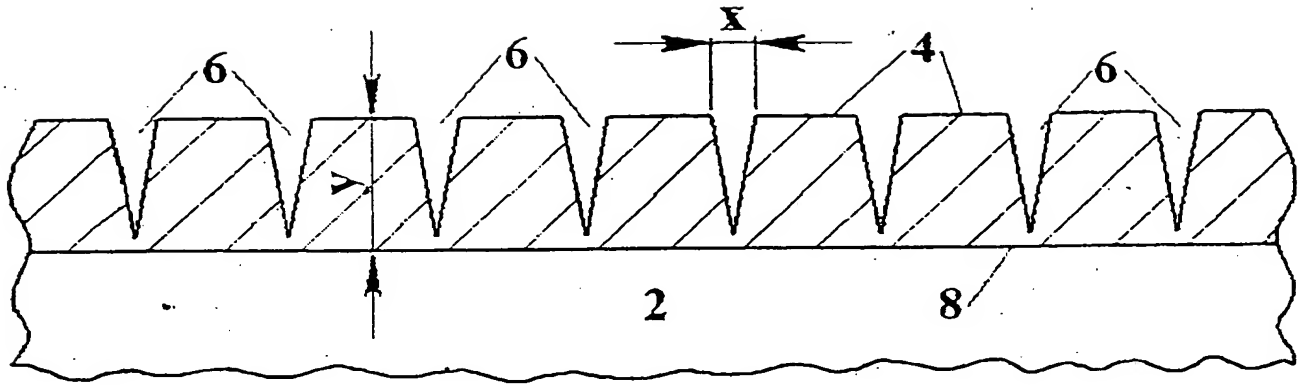


Fig. 1

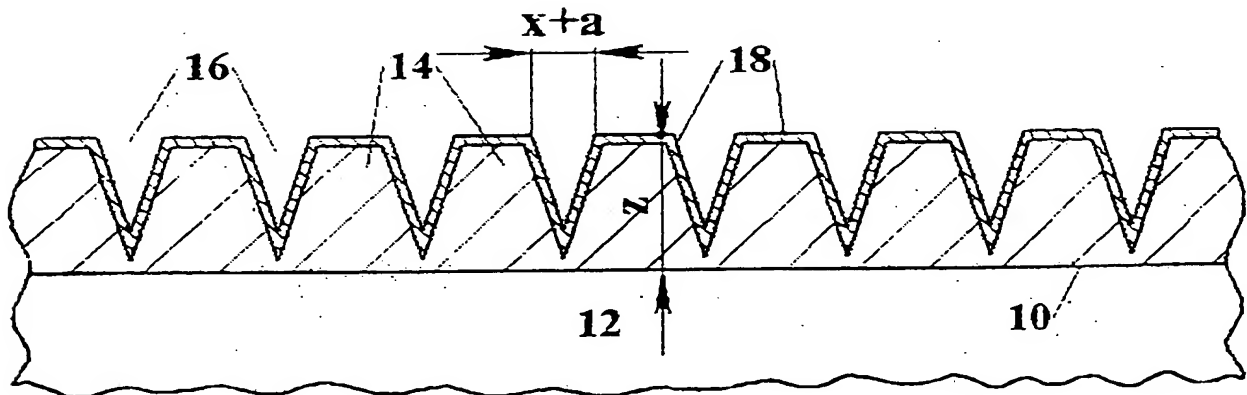


Fig. 2

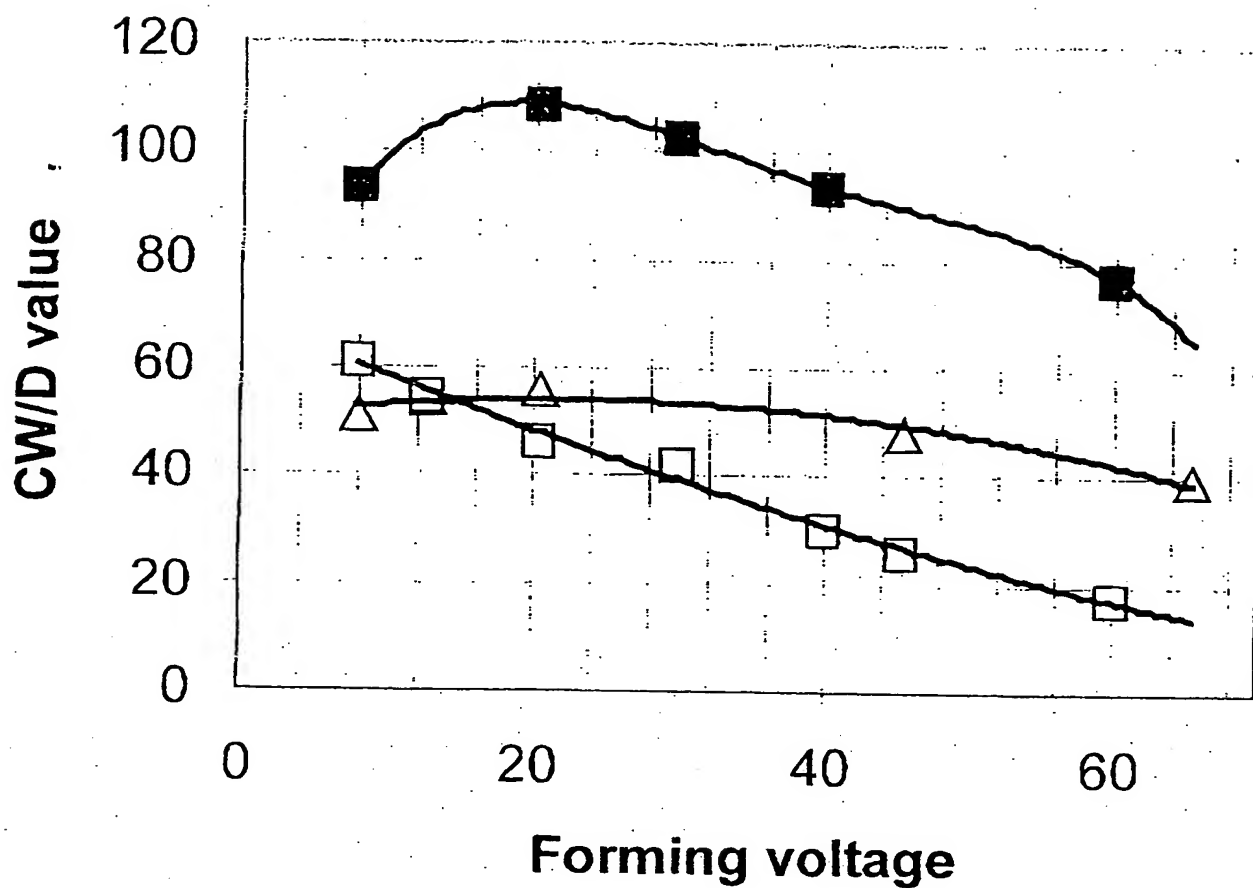


Fig 3

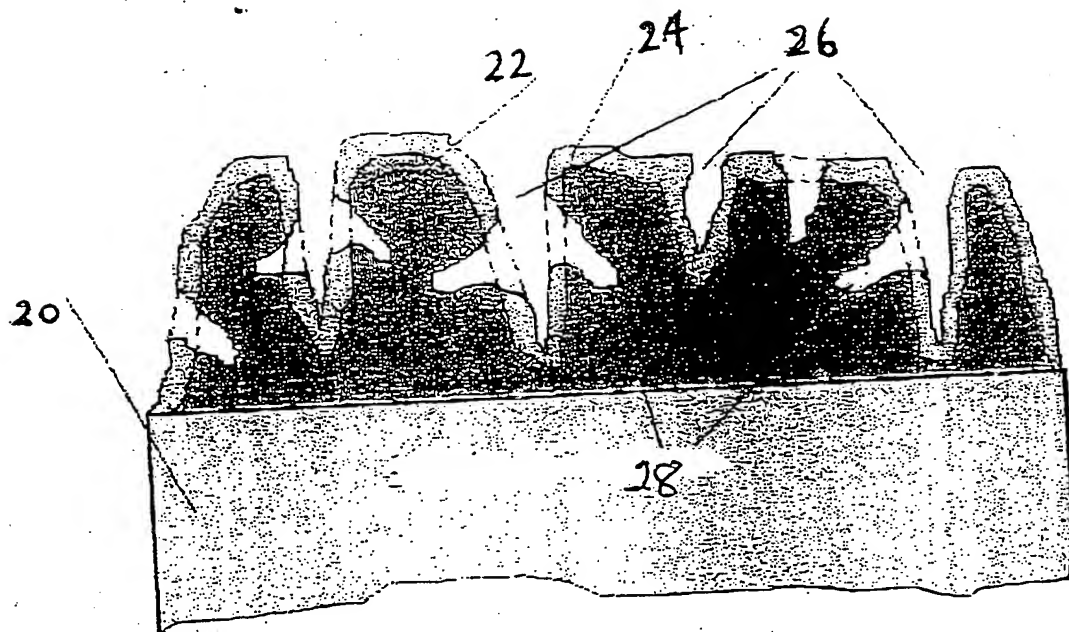


Fig. 4